# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION / AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited. |
| 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>NRL Memorandum Report 5446 | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Naval Research Laboratory<br>6b. OFFICE SYMBOL (If applicable)<br>Code 7521 | 7a. NAME OF MONITORING ORGANIZATION |
| 6c. ADDRESS (City, State, and ZIP Code)<br>Washington, DC 20375-5000 | 7b. ADDRESS (City, State, and ZIP Code) |
| 8a. NAME OF FUNDING / SPONSORING ORGANIZATION<br>Office of Naval Research<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c. ADDRESS (City, State, and ZIP Code)<br>Arlington, VA 22217 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. 61153N<br>PROJECT NO. RR021-05-42<br>TASK NO.<br>WORK UNIT ACCESSION NO. DN880-011 |

11. TITLE (Include Security Classification)
Distributed Reservation-Based Code Division Multiple Access

12. PERSONAL AUTHOR(S)
Wieselthier, J.E. and Ephremides, A.*

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Interim | FROM ________ TO ________ | 1984 November 2 | 24 |

16. SUPPLEMENTARY NOTATION
*University of Maryland, College Park, MD 20742

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Multiple access<br>Communications networks<br>Code Division Multiple Access |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The use of spread spectrum signaling, motivated primarily by its antijamming capabilities in military applications, leads naturally to the use of Code Division Multiple Access (CDMA) techniques that permit the successful simultaneous transmission by a number of users over a wideband channel. In this paper we address some of the major issues that are associated with the design of multiple access protocols for spread spectrum networks. We then propose, analyze, and evaluate a distributed reservation-based multiple access protocol that does in fact exploit CDMA properties. Especially significant is the fact that no acknowledgment or feedback information from the destination is required (thus facilitating communication with a radio-silent node), nor is any form of coordination among the users necessary.

| | |
|---|---|
| 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>J. E. Wieselthier | 22b. TELEPHONE (Include Area Code) (202) 767-3043<br>22c. OFFICE SYMBOL Code 7521 |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

**NRL Memorandum Report 5446**

# Distributed Reservation-Based Code Division Multiple Access

J. E. WIESELTHIER AND A. EPHREMIDES*

*Communication Systems Engineering Branch*
*Information Technology Division*

**University of Maryland*
*College Park, MD 20742*

November 2, 1984

**NAVAL RESEARCH LABORATORY**
**Washington, D.C.**

CONTENTS

# DISTRIBUTED RESERVATION-BASED CODE DIVISION MULTIPLE ACCESS

## INTRODUCTION

There are many applications in which a number of geographically distributed users transmit messages intermittently to a single destination over a common ground radio or satellite channel, as shown in Figure 1. Examples of these include packet radio [1], naval intra task force communication [2,3], cellular telephony [4], and other mobile radio network systems. In such networks, a set of rules, known as a multiple access protocol must be employed by each user to govern its access to the channel.

A great deal of attention has been paid to the study of multiple access protocols. A relatively novel aspect of this field is the case in which some form of spread-spectrum signaling is used that enables the users to access the channel on a so-called code-division basis. Then new degrees of freedom in the design of multiple access protocols become available.

In this paper we address some of the major issues that are associated with the design of multiple access protocols for spread spectrum networks. We then propose, analyze, and evaluate a distributed reservation-based multiple access protocol, originally introduced in [5], that does in fact exploit Code Division Multiple Access (CDMA) properties.

## THE MULTIPLE ACCESS PROBLEM

One approach to the multiple access problem is the use of Time Division Multiple Access (TDMA), under which each user is cyclically assigned a slot of fixed duration. The fixed structure of TDMA is very efficient (in the sense of small delay and high channel utilization) when the users are transmitting at a uniform high rate. It is inefficient, however, when one or more users are idle, because channel capacity is then wasted. Similarly, TDMA is also inefficient when the data traffic is bursty (e.g., Poisson in nature rather than uniform) because it is unable to adapt to changing user demands.

Manuscript approved August 10, 1984.

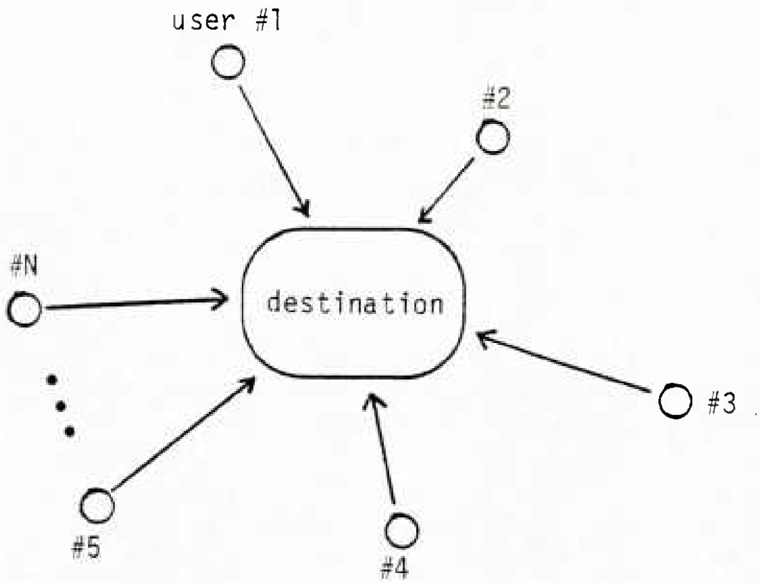



Fig. 1 Population of independent users communicating to a single destination over a common radio or satellite channel.

The first channel access protocol designed for bursty traffic was the ALOHA technique, under which a user transmits a packet immediately upon its generation. As a result of the random nature of the process by which packets are generated, it is possible for the transmission of two or more packets to overlap, in which case all packets involved in the "collision" are assumed to be destroyed. These packets are then retransmitted after a random time delay.

ALOHA may perform very well at low throughput rates, in terms of average delay time. However, an ALOHA system is inherently unstable, and as a result of statistical fluctutations in the traffic generation process it can go into saturation (i.e., a condition in which the successful transmission rate, and therefore throughput, approaches zero) even when the packet input rate is relatively low.

A great deal of creative thinking has been devoted to the design of multiple access protocols in recent years, as is discussed in a number of survey articles [6,7] and textbooks [8-10]. The goal of these studies has been to develop schemes that produce low delay and high throughput (and therefore high bandwidth utilization), while guaranteeing stability. Examples of these protocols include contention resolution procedures such as the Capetanakis tree algorithm, channel sensing schemes such as Carrier Sense Multiple Access (CSMA), and reservation schemes, as well as hybrids of two or more of these classes. Reservation schemes, to be discussed in detail shortly, are often attractive

because stable operation can be maintained at relatively high throughput levels, provided that a reservation mechanism can in fact be implemented.

All of these schemes have represented an approach to the problem of multiple access that is based strictly in the "time domain." In this paper we depart from the constraints of purely time-domain protocols, and present, analyze, and evaluate a distributed reservation scheme that takes advantage of the quasi-orthogonality property that can be achieved through the use of spread spectrum Code Division Multiple Access (CDMA) signaling. This property permits the successful reception of a packet despite the simultaneous transmission by other users. The reservation scheme is in fact totally distributed in that it does not require the transmission of acknowledgment or feedback information from the destination to the users. Furthermore, no coordination among the users is required, nor do they even have to monitor each others' transmissions.

The use of CDMA techniques in conjunction with multiple access protocols is a relatively new area, and so we review the main principles of CDMA as they relate to the design of such schemes. To provide further background we also discuss reservation schemes in general. We then present the system model for the distributed CDMA-based reservation scheme, followed by an analysis and performance evaluation.

## CODE DIVISION MULTIPLE ACCESS TECHNIQUES

Spread spectrum signaling, normally used because of its antijamming capability, leads naturally to the use of Code Division Multiple Access techniques [11,12]. A spread spectrum system is one in which the transmitted signals are spread over a frequency band that is much wider than the minimum bandwidth required to transmit the information. For example, in a frequency hopping (FH) system the transmitter hops from one frequency bin or subband to another, transmitting a narrowband signal at each hop; the FH pattern is a pseudorandom sequence that typically provides a degree of immunity from jamming. The receiver must use the same hopping pattern as the transmitter.

In FH-CDMA systems the code corresponds to the FH pattern. Selective addressing is achieved by the transmitting node through the use of a code associated with a particular destination. In this paper we are more interested in the selective reception capability, which is the ability of a receiver to monitor the code associated with any particular transmitting user, despite the presence of other signals on the channel.

For the purpose of analysis we assume that each hopping pattern is random, and those corresponding to different codes are independent of each other. It is therefore possible for two or more users (using different hopping patterns) to transmit

simultaneously in the same frequency bin, resulting in loss of data. The loss of data caused by such "frequency hits*" can be handled via the use of error control coding. The number of users that can share a wideband channel by means of CDMA techniques and the resulting performance depend on the modulation/coding scheme, channel characteristics, and receiver implementation. This problem has been investigated, but still requires further study (see e.g., Pursley [13,14], Hajek [15], and Wieselthier and Ephremides [16]).

There is an analogy between TDMA and CDMA. In the case of TDMA the channel is shared by assigning a distinct time slot to each user, thus ensuring that the users don't interfere with each other; the users are therefore orthogonal in the time domain. In the case of FH-CDMA a distinct code may be assigned to each user. A number of users can transmit simultaneously on different codes, with no individual user able by itself to cause significant interference to any other user; however, the combined effect of a sufficiently large number of users can disrupt each other's communication. There is thus only a <u>quasi-orthogonality</u> among users in the code-domain. A very large number of quasi-orthogonal codes can be defined. Performance will be acceptable as long as not too many signals (using different codes) are transmitted simultaneously.**

Note that we use the term CDMA to refer to a class of multiple access techniques that use the CDMA multi-user channel property. Although CDMA itself permits a number of signals to share a wideband channel simultaneously, we retain the constraint that a user can correctly receive at most one signal at a time. It is therefore necessary to develop multiple access protocols that operate in the joint time-code domain by taking advantage of the CDMA multi-user channel property, while living within the constraints imposed by the use of spread spectrum signaling.

---------------

* These hits involve fractions of packets in this case, in contrast to the usual case of time-domain multiple access schemes in which collisions result in the destruction of entire packets.

---------------

** In some cases it is possible to have a set of orthogonal codes in a FH-CDMA system. This means that no two users ever transmit in the same frequency bin simultaneously. Clearly, the number of codes in such a system can be no greater than the number of frequency bins. In addition, very accurate timing is required to maintain synchronization among the hopping patterns corresponding to different codes. In contrast, most analyses of quasi-orthogonal CDMA systems assume that there is no synchronization among the various codes, although of course the receiver must be synchronized to the particular code that it is monitoring.

Our discussion of CDMA is far from complete. We have addressed only those issues that relate to the design of the distributed reservation scheme that we present in this paper; a more thorough discussion is presented in [2]. In particular, we have not discussed the "capture" effect that permits the receiver to lock onto the first to arrive of several signals that are using the same code [17,18]. This property, like the multi-user channel capability, provides a degree of flexibility in the design of multiple access protocols that is not found in purely time-domain schemes. On the other hand, we have not addressed some of the features of spread spectrum signaling that make it difficult to design multiple access protocols, e.g., the difficulty of obtaining an estimate of channel activity, similar to that which is used in CSMA, or alternatively the type of channel monitoring that is used in the control of some ALOHA-type schemes. In addition, the problem of acquisition of synchronization of spread spectrum signals will have a significant impact, primarily in terms of the time required for synchronization, and thus the overhead required for synchronization as a fraction of the packet size.

## RESERVATION SCHEMES

Before we present the system model for the distributed CDMA reservation-based channel access scheme we first discuss reservation schemes in general. It is clear that if each terminal knew the number of packets waiting in queue at every other terminal at all times, it would be possible to schedule transmissions so that the channel would never be idle when some terminal had a packet ready to transmit; it also follows that at most one user would transmit in any slot. If reservations for these packets could be made without expenditure of bandwidth and with zero time delay, we would be able to obtain this ultimate performance limit for multiple access schemes. Such an idealized scheme is called perfect scheduling, and represents an ideal First-In-First-Out (FIFO) queueing system. However, in practice each reservation scheme suffers the consequences of allocating bandwidth for making the reservations, as well as the time delay associated with the reservation process.

In typical reservation schemes (such as Roberts' Reservation scheme [19]), each terminal first transmits reservation minipackets (which are much smaller than the actual information packets) to request the assignment of a time slot for each packet in its queue. Upon the successful transmission of a reservation minipacket, the corresponding information packet(s) will in effect join a common queue from which they may be transmitted, without danger of collision and according to whatever service discipline has been chosen (e.g., first come first served).

Under ideal conditions (i.e., a noiseless channel where all users are within communication range of each other and can thus monitor each other's reservation requests) no central controller

would be needed. The Interleaved Frame Flush-Out (IFFO) protocols [20], for example, are a class of schemes in which transmission schedules are generated by the users in a distributed fashion, based upon the reservation requests of the population of users. All scheduling decisions could be made unambiguously by the users themselves in a distributed fashion because they would have the same data base after receiving the reservation transmissions. In many realistic situations, however, as a consequence of potential channel errors or equipment malfunction it cannot be assumed that all users have the same information. Inconsistent transmisision schedules can then be generated resulting in the simultaneous transmission by two or more users. Such collisions are usually assumed to destroy all packets that are involved. Therefore a central controller will usually be needed to allocate slots to the users requesting them to ensure that at most one user transmits in any slot.

In this paper we present, analyze, and evaluate a distributed reservation scheme that can in fact operate in an environment of noisy channels characterized by lack of complete connectivity. It is especially important that the control of a channel access scheme be distributed when multiple users are attempting to communicate with a central station that cannot communicate back to the users and thus cannot provide schedules. Such a situation can occur when the destination is required to maintain radio silence (either by operational doctrine or as a result of transmitter power limitations or malfunction) or if the link from the destination back to the multiple access users is jammed.

## SYSTEM MODEL FOR DISTRIBUTED RESERVATION SCHEME

We assume fixed length packets and a fixed length slotted frame structure (L slots per frame), as shown in Figure 2. As is typical of slotted systems the slot duration is equal to the length of a packet, and all packet transmissions start at the beginning of a time slot. Each user is assumed to have at most one packet to transmit in any frame. Spread spectrum signaling is used, thereby permitting the use of CDMA techniques, which permit the correct reception of signals despite the simultaneous transmission by other users. As we have already noted, a receiver is assumed to be able to monitor only one of these signals at a time, however, as in standard multiple access systems.

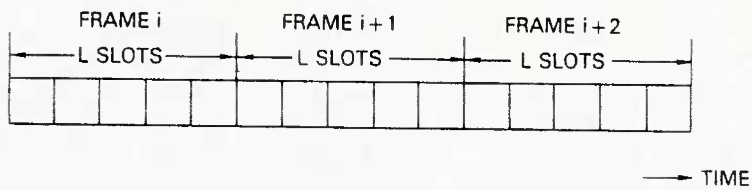



Fig. 2 Slotted frame structure.

Typically a contention-free reservation process is assumed. One can be implemented if the size of the total user population is not too great by designating the first slot of each frame as a reservation slot and dividing it into TDMA minislots. Alternatively, a separate reservation channel could be implemented. Contention-based reservation procedures are also sometimes considered. In such cases only the reservation minipackets (which are much smaller in length than message packets) are competing for channel access, and significantly higher data throughput can be maintained than in a purely contention-based channel access scheme. The impact on performance of contention in the reservation process is not investigated here.

Here we propose a reservation procedure that is quite different from conventional schemes. In the first version considered each user with a packet to transmit chooses one of the L slots in the frame at random. He sends a reservation minipacket that consists not only of a declaration of intent to transmit in the coming frame, but in addition the actual slot number in which he will transmit. Since the users are uncoordinated it is possible for two or more of them to choose the same slot. The receiver, however, has full knowledge of the transmitters' intentions. In conventional "time-domain" schemes such interference would result in collisions that destroy each packet that is involved. By the use, however, of spread spectrum code division techniques the simultaneous sharing of a wideband channel by a number of signals is possible. Whenever two or more users declare their intent to transmit in the same slot it is up to the receiver to decide which of these signals it will in fact monitor. Initially it is assumed that the codes are orthogonal, so that any number of users can be tolerated in the same slot. In this case there is a successful transmission in any slot chosen by one or more users. We later consider the more realistic case of quasi-orthogonal codes.

By analogy to standard reservation schemes we sometimes use the term "assigned slot" to refer to the slot in which a user is successful, i.e., is being monitored, despite the fact that explicit assignments are not made. The ability to receive one signal correctly, despite the presence of others, results in considerable performance improvement as compared with conventional time-domain ALOHA-type schemes, as we shall demonstrate.

A sample realization of a frame of protocol operation is illustrated in Figure 3 for the simple case of frame length L = 5 slots and M = 5 users transmitting in the frame. Only the actual data slots are shown, and not the reservation slot (or subchannel). The slots chosen by the users have been shaded. Users #1, #3, and #5 have chosen slots #2, #1, and #5 respectively; all of these users are successful because they are the only ones to transmit in their respective slots. Users #2 and #4, however, have both chosen slot #4. Only one of these is successful; the decision of whom to monitor is left up to the destination.

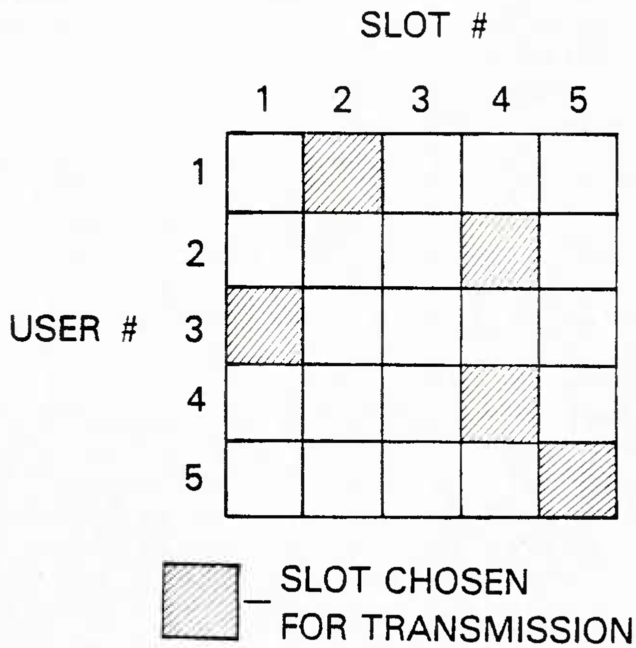



Fig. 3 Sample realization of a frame of protocol operation for L = 5, M = 5.

There are two basic ways to handle unsuccessful packets. They either may be retransmitted at a later time (e.g., in the next frame) or they may be simply dropped from the users' buffers. The former approach is the one most often taken in contention-based schemes. However, we have assumed that there is no feedback information of any type transmitted by the destination or among the users. The success or failure of individual transmissions cannot be determined, and so there is no information available on which to base a decision to retransmit. We thus assume that unsuccessful packets are dropped from the user's buffer, and therefore lost. The probability of packet loss is easily evaluated in the course of evaluating channel performance. (We note that the case in which acknowledgment information, but not scheduling, is available can also be modeled by the approach of this paper.)

The basic reservation scheme has been extended by permitting each transmitting user to designate several (say Q) slots in which he will transmit the <u>same</u> packet, thereby providing what

one might call packet diversity. The destination node, after receiving all of these reservations, will attempt to generate a monitoring schedule that maximizes the number of distinct packets it receives correctly. Alternatively, a priority structure can be implemented in which certain users are more likely to be monitored, while others are monitored only if the high priority users are taken care of. In this paper we use the expected throughput, i.e., the expected number of successful packets per slot, as the performance criterion.

We can consider an extreme case in which each transmitting user transmits in all L slots of the frame. If the spread spectrum codes employed by each user were truly orthogonal, then such a scheme would provide optimum performance. However, only a quasi-orthogonality normally exists among such codes, and channel errors will result if too many signals attempt to share the channel simultaneously. The optimum value of the packet diversity parameter Q therefore depends on the degree of other-user interference that can be tolerated.

We first consider the case in which other-user interference is not troublesome (i.e., any number of other simultaneous users can be tolerated). One packet is thus successful in every assigned slot. We then introduce the effects of other-user interference by means of a simplified model in which a packet is never received correctly if the number of other users in its assigned slot is equal to or greater than some threshold, but always received correctly if the number is lower than the threshold. A more realistic model would be based on a probability of success that is a function of the number of users transmitting in the slot. Important considerations include the modulation/coding scheme, channel characteristics, and receiver implementation (see e.g., [13,14,16]). The simplified interference model used here permits the presentation of the basic concept of operation of the distributed reservation protocol without the added complication of making specific assumptions about the signaling scheme and receiver structure.

## ANALYSIS OF DISTRIBUTED RESERVATION SCHEME

We evaluate the conditional probability distribution of the number of successful transmissions in a frame consisting of L slots, given that M users transmit packets, and each of these transmits its packet in Q slots chosen at random. We do not consider the mechanism used to make reservations; it is assumed that the destination receives error free reservation information from all users without incurring any overhead costs. We also do not consider the statistics of the arrival process. In this section we consider only the case of perfectly orthogonal codes; i.e., a packet that is monitored is received correctly regardless of the number of other users transmitting in the same slot. We later consider the case in which a packet is received correctly if and only if the number of other users transmitting in the slot does not exceed some threshold.

We first examine the case of $Q = 1$, i.e., each packet is transmitted exactly once in the frame. This case can be treated exactly. One way to do so is to use combinatorial techniques to determine the probability distribution for the number of non-empty time slots (see e.g., [21]). We consider, however, the following Markov chain approach, which can be extended to obtain a lower (pessimistic) bound on system performance for $Q>1$.

The problem is formulated as follows. We are given L slots and M users, each of which transmits in exactly one slot. The number of successful packets is equal to the number of slots in which one or more packets are transmitted. We approach this problem from the viewpoint of the M users, each of which in turn independently places a packet into one of the L time slots (rather than from a slot-by-slot viewpoint in which we would consider how many users transmit in each slot). As each user picks a slot we determine whether this slot has already been chosen by another user. We define the transition probability for the number of successes in the frame as the number of users is increased from k to k+1, for $1 < k \le M-1$:

$$P(n|i) = \Pr(n \text{ successes by first } k+1 \text{ users} | \text{ given } i \text{ successes by first } k \text{ users}). \tag{1}$$

Clearly, the only possible transitions from i successes are to $n = i$ and $n = i+1$. An unsuccessful transition occurs if user k+1 chooses one of the i slots chosen by the first k users:

$$P(i|i) = i/L. \tag{2}$$

A successful transition occurs if user k+1 chooses one of the (L-i) slots not chosen by the first k users:

$$P(i+1|i) = 1 - i/L. \tag{3}$$

We define,

$$p_j(i) = \Pr(i \text{ successes in first } j \text{ user attempts}). \tag{4}$$

This probability can be expressed in terms of the transition probabilities as,

$$p_j(i) = p_{j-1}(i)P(i|i) + p_{j-1}(i-1)P(i|i-1), \tag{5}$$

with initial condition $p_1(1) = 1$. The distribution for $p_j(i)$ is evaluated recursively until we obtain,

$$p_M(i) = \Pr(i \text{ successes in first } M \text{ user attempts})$$

$$= \Pr(i \text{ successes in frame}). \tag{6}$$

For $Q > 1$ the distribution for the number of successful transmissions depends on the strategy used by the destination to determine whom it will monitor in each slot. It is difficult to evaluate this distribution for an optimal monitoring strategy. The case of $Q = 1$ was quite simple because the criterion for successful packet transmission was simply whether or not the user's slot had already been chosen. In Figure 4 we illustrate the difficulty for $Q > 1$ in extremely simplified form for the case of $Q = 2$, $L = 3$, and $M = 3$. In this example, if the destination decides to monitor user #1 in slot #1 and user #2 in slot #2 then no assignment is possible for user #3. If, however, user #1 is monitored in slot #4, then slot #1 would be available for user #3. For large values of L, M, and Q it is considerably more difficult to create an optimum set of slot assignments (i.e., one that maximizes the number of successful packets). We have therefore considered a non-optimal scheme, that is amenable to analysis, which we describe as follows.

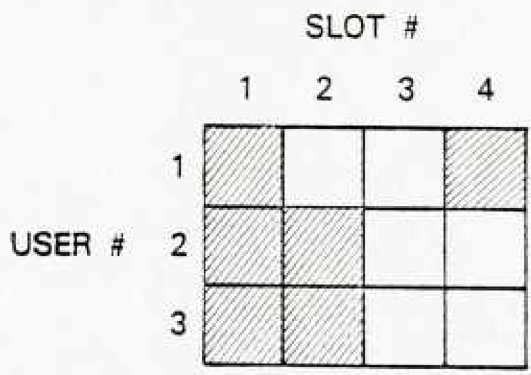



Fig. 4 Simplified illustration of the difficulty of slot assignment.

In the non-optimal scheme, which we consider for $Q > 1$, the destination assigns slots before he has complete knowledge of the reservations for all users. As in the case of $Q = 1$ we consider the transition probabilities as we add users, until a total of M users have been considered. The first user ($k=1$) is always successful. The destination chooses one of his Q slots at random; his remaining Q-1 slots are treated as empty slots. No effort is made to coordinate his assignment with those of the other users that follow him in sequence. Therefore some inefficiencies can result as discussed above. The analysis therefore provides a pessimistic estimate of the system performance as compared with that of a more intelligent decision maker.

Note that the first Q users are always successful, even if they all choose the same set of Q slots. In general, user k will be successful if one or more of his Q slots has not already been assigned to another user. The destination randomly assigns one of these (not previously assigned) slots to him. Therefore,

$$P(i|i) = \begin{cases} \dfrac{i\,(i-1)\,\ldots\,(i-Q+1)}{L\,(L-1)\,\ldots\,(L-Q+1)}, & i \geq Q \\ 0 & i < Q \end{cases} \tag{7}$$

and,

$$P(i+1|i) = 1 - P(i|i). \tag{8}$$

We again use the recursion defined by eq. (5) to evaluate the probability distribution for the number of successful transmissions in the frame.

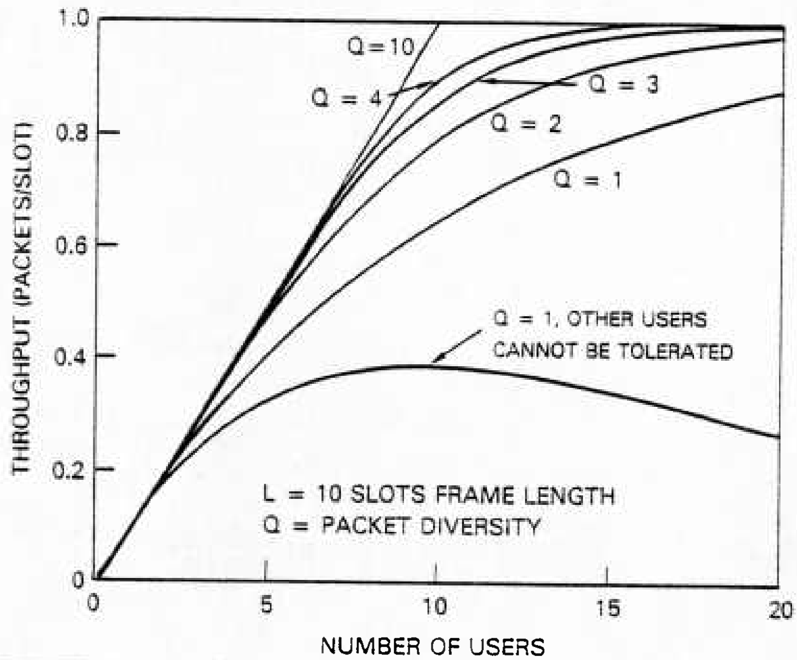



Fig. 5 Throughput performance of distributed reservation scheme; any number of other users can be tolerated in same slot.

## PERFORMANCE EVALUATION

### Case 1: Orthogonal Codes

We have used as a performance criterion the throughput, which we define as the expected number of successful packets received per slot. Any overhead caused by the reservation process is neglected, but could easily be added to our model for any of a number of specific reservation schemes. In Figure 5 we illustrate throughput as a function of the number of users M for packet diversity values of Q = 1, 2, 3, and 4. The frame length is L = 10 slots. These performance curves were generated under the assumption that the spread spectrum codes are in fact

orthogonal, thus permitting other-user interference to be ignored. An upper bound on throughput (corresponding to the case of $Q = L$, i.e., all users transmitting in every slot) is also provided. Throughput of course increases as $Q$ increases, with the most significant increase occurring as $Q$ is increased from 1 to 2. The throughput of an ALOHA-type system (i.e., $Q = 1$, but transmission is unsuccessful if two or more users transmit in the same slot) is also shown to illustrate the considerable improvement that is obtained as a result of the ability to tolerate other-user interference by means of spread spectrum CDMA signaling.

An alternative performance criterion, which we do not consider here, is the probability of successful packet delivery, or equivalently probability of packet loss.

Case 2: Quasi-orthogonal Codes

We now consider the effect of other-user interference on channel throughput. A model for such interference is presented in [13,14] for the case of frequency hopped signaling with Reed-Solomon coding used to correct errors caused by frequency hits; a packet is received correctly as long as the number of symbol errors (or in some cases symbol erasures) is not too great. The occurrence of such symbol errors, and thus the probability of correct packet reception, depends on the modulation/coding scheme, number of users, number of frequency bins, channel characteristics, and availability (or lack) of side information (i.e., knowledge of which hops have been corrupted by hits).

For example, for the case in which a packet consists of a single RS-(31,15) codeword, with one 32-ary (5-bit) symbol transmitted per hop, 100 frequency bins, random asynchronous hopping patterns, a noiseless channel (i.e., the only source of errors is other-user interference) and no side information, the packet error probability is approximately 0.01 (0.1) when 7 (11) users transmit over the channel simultaneously. If the noise-induced probability of 32-ary symbol error (i.e., symbol error probability in the absence of other-user interference) is 0.1, then the packet error probability is approximately 0.01 (0.1) when 2 (6) users transmit simultaneously.

In this paper, to avoid the need to assume a specific modulation/coding format, we have used a simplified model for other-user interference in which a packet is never received correctly if the number of other users transmitting in the same slot is equal to or greater than some threshold, but always received correctly if it is lower than the threshold.

We also note that although it may be possible for the destination to change slot assignments to avoid slots with many users, our model assumes use of the same slot assignments obtained in the orthogonal code (no interference) case. In this sense our model is pessimistic, because an intelligent receiver might be able to make such a decision.

An exact system description is difficult to obtain. We would need the conditional joint probability distribution for the number of assigned slots in which i users transmit, for $i = 1,2,\ldots,M$. We have simplified the model by assuming a Bernoulli transmission sequence of rate Q/L at each user that transmits in the frame in every slot. This Bernoulli model results in the same average number of users transmitting per slot as in the original system model. Under this assumption the probability distribution for the number transmitted in each slot is then

$$q(t) = \Pr(t \text{ users transmit in a slot} \mid M \text{ users})$$

$$= \binom{M}{t}\left(\frac{Q}{L}\right)^{t}\left(1 - \frac{Q}{L}\right)^{M-t} \qquad (9)$$

We actually need

$$q(t \mid A) = \Pr(t \text{ users transmit} \mid \text{given } A,\ M \text{ users}) \qquad (10)$$

where,

$$A = \text{event that the slot is assigned to some user.} \qquad (11)$$

We make the simplifying assumption that the probability of a slot being assigned to some user (i.e, for a user to be monitored by the destination in that slot) is independent of the number of users transmitting in that slot, provided that at least one actually transmits. Therefore,

$$q(t \mid A) = q(t)/(1-q(0)). \qquad (12)$$

The probability of successful packet reception, given that a slot is assigned, is equal to the probability that fewer than T users transmit in the slot, i.e.,

$$\Pr(t<T \mid M) = \sum_{t=1}^{T-1} q(t \mid A). \qquad (13)$$

An approximation for expected throughput is obtained by multiplying the values presented in Figure 4 by this probability.

Define I to be the number of other users that can be tolerated in a slot. Clearly, $I = T - 2$. In Figures 6 and 7 we illustrate throughput performance for threshold values of $I = 0$ and 2, respectively, again for the case of $L = 10$. Figure 5, which represents the case in which other-user interference can be ignored, corresponds to $T > M$, or equivalently $I \geq M-1$. We see that the optimum value of Q, for a given threshold $\bar{I}$, depends on the number of users. For the case of $I = 0$, however, in which the presence of one or more other users causes a packet error (as in ALOHA) a packet diversity value of $Q = 1$ is best for any number of users.

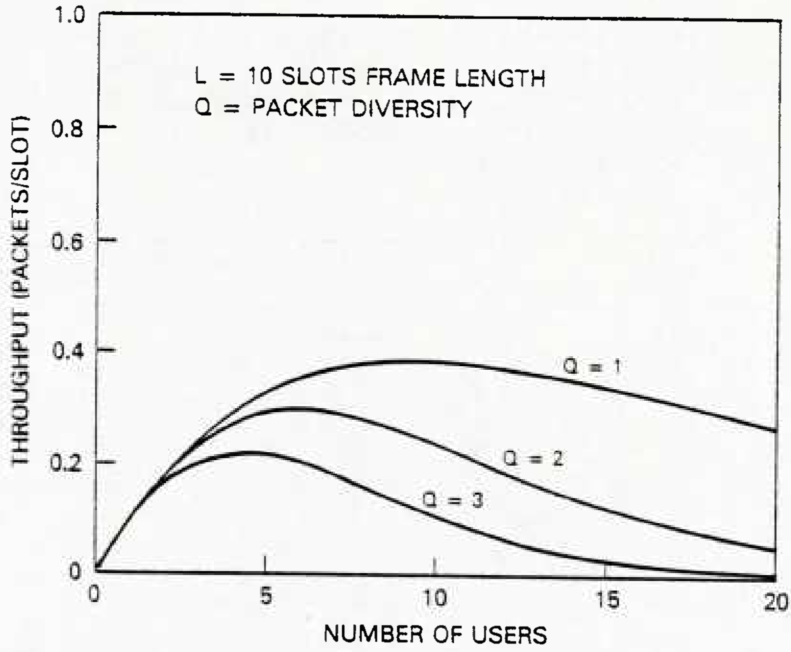



Fig. 6 Throughput performance of distributed reservation scheme; no other users can be tolerated in same slot.

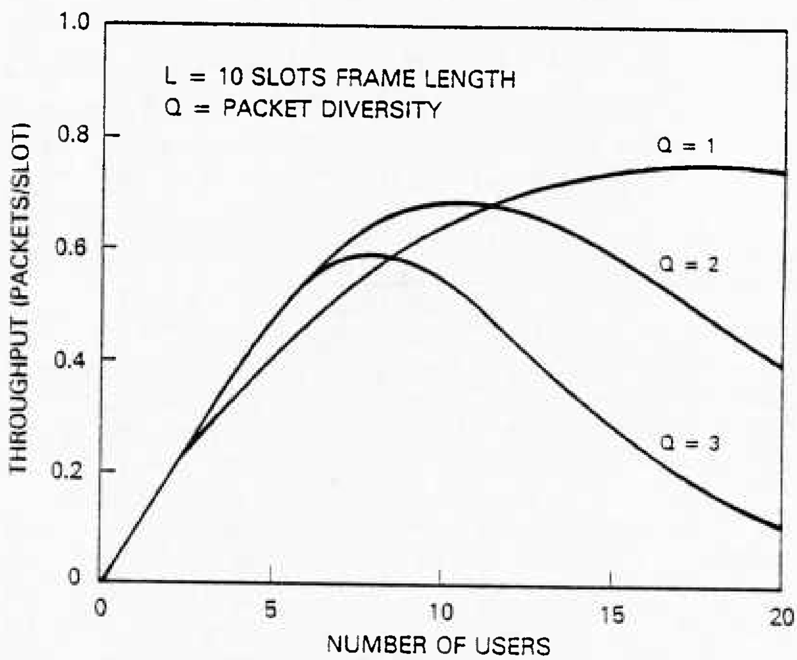
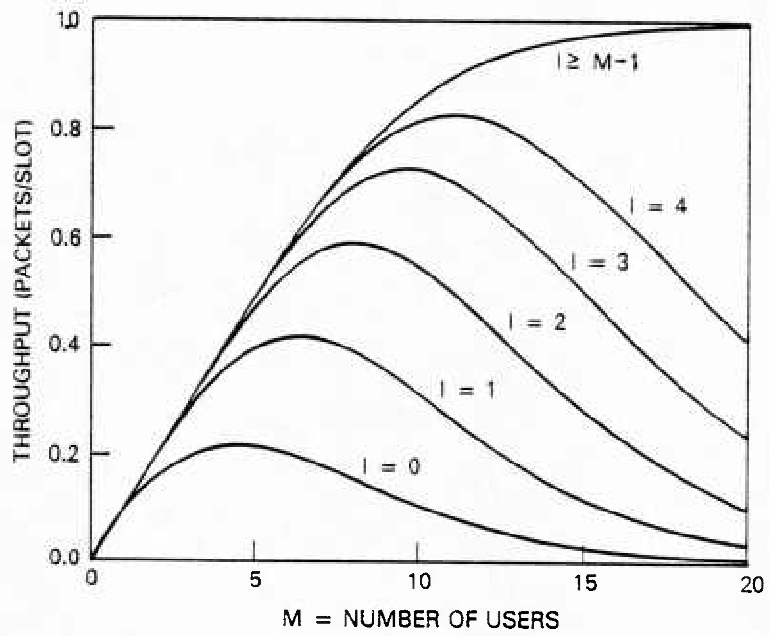



Fig. 7 Throughput performance of distributed reservation scheme; two other users can be tolerated in same slot.

In Figure 8 we illustrate throughput performance for Q = 3 as I is varied from 0 to 4. As I is increased the throughput increases, until it reaches the limiting case for $I \geq M-1$, which is in fact the orthogonal code case in which other user interference can be neglected.




L = 10 SLOTS FRAME LENGTH

Q = 3 = PACKET DIVERSITY

Fig. 8 Throughput performance of distributed reservation scheme for several levels of tolerable interference.

A NOTE ON ROBUSTNESS AND SURVIVABILITY

In our analysis we have assumed that the destination receives all reservations correctly, and is therefore able to construct a (not necessarily optimal) monitoring schedule. We now consider qualitatively the effect of incomplete or erroneous reservation information. First, consider the case of missed reservations. Each user will transmit in the Q slots he has selected independent of whether or not his reservation is actually received. The destination will then simply create a listening schedule consisting of as many of the users it has received reservations from as is possible. The loss of one or more reservations will tend to make it easier to schedule those for whom reservations have been received, because there are fewer users to schedule. Thus, failure to receive reservations will usually adversely affect only those whose reservations are not successful, and not the remainder of the population. It is straightforward to model a system in which reservations are

correctly received with some probability, rather than the perfectly reliable reservation mechanism assumed in this paper.

A crucial feature of the distributed reservation protocol is that the destination does not have to broadcast schedules, and can thus maintain radio silence. Therefore, in order to disrupt protocol operation one must disrupt the actual link from user to destination, since there is no (potentially weak) feedback or acknowledgment channel from destination to users. Another feature aiding survivability is the fixed frame length. One does not have to monitor either data traffic or control traffic to know frame boundaries.

## AN EXTENSION TO MULTIPLE DESTINATIONS

We have thus far considered a single destination to whom all packets are directed. We now consider multiple destinations, as shown in Figure 9. We assume that some of the users communicate with more than one destination, and that not all users are within communication range of all destinations. As in the single destination case the use of multiple transmissions permits greater flexibility in slot assignment. It is certainly possible for one destination to monitor one transmission of a packet while another destination monitors one of the other redundant transmissions.

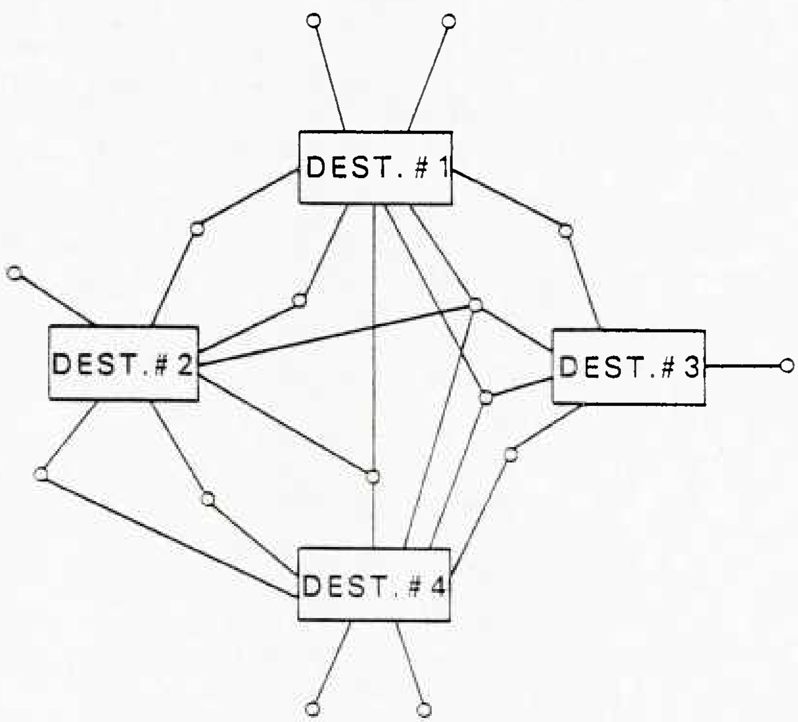



Fig. 9 Sample multiple destination geometry.

In contrast, we can consider a conventional centrally controlled reservation scheme (i.e., one in which the destination prepares and distributes schedules to the users) operating in a multiple destination environment. In such a system multiple transmissions from users would often be required (i.e., one to each destination), unless the destinations were able to coordinate their listening schedules, a task which requires the exchange of information among the destinations. Such coordination would have to be done every frame because of the assumed bursty nature of the traffic process, and in many cases would not be feasible. Furthermore, to do so would violate the assumption of radio-silence. The distributed reservation scheme, on the other hand, is very well suited for communication from a population of bursty users to a group of geographically separated uncoordinated destinations.

## CONCLUSION

The problems of Code Division Multiple Access represent a relatively new facet of the field of multiple access protocols, especially for the case of mobile users and radio channel applications. Many of the studies so far have focused on the analytical modeling of the spread-spectrum signaling schemes that make CDMA possible [13,14]. Not much attention has been paid to the exploitation of the new degrees of freedom that become available to the protocol designer through the use of CDMA. In this paper we have tried to illustrate the potential of such exploitation by focusing on a distributed reservation scheme that does in fact take advantage of such properties. This scheme is especially well suited to cases in which the receiver must be radio silent or in which feedback information in the form of acknowledgment or other messages cannot reach the transmitting users reliably.

Much work is still needed in this direction in order to translate the potential capabilities of CDMA into useful multiple access protocols in practice.

## REFERENCES


1. R. E. Kahn, S. A. Gronemeyer, J. Burchfiel, and R. C. Kunzelman, "Advances in Packet Radio Technology," Proc. IEEE, vol. 66, pp. 1468-1496, Nov. 1978.

2. J. E. Wieselthier, D. J. Baker, A. Ephremides, and D. N. McGregor, "Preliminary System Concept for an HF Intra Task Force Communication Network," Naval Research Laboratory, Washington, DC, NRL Report 8637, Aug. 9, 1983. (AD-B077 416L)

3. D. J. Baker, A. Ephremides, and J. A. Flynn, "The Design and Simulation of a Mobile Radio Network with Distributed Control," IEEE Journal on Selected Areas in Communications, vol. SAC-2, pp. 226-237, January 1984.

4. N. Ehrlich, "The Advanced Mobile Phone Service," IEEE Communications Magazine, vol. 17, pp. 9-15, March 1979.

5. J. E. Wieselthier and A. Ephremides, "A Distributed Reservation Scheme for Spread Spectrum Multiple Access Channels," Proc. GLOBECOM'83, pp. 659-665.

6. F. A. Tobagi, "Multiple Access Protocols in Packet Communication Systems," IEEE Trans. Commun. vol. COM-28, pp. 468-488, April 1980.

7. S. S. Lam, "Satellite Packet Communication--Multiple Access Protocols and Performance," IEEE Trans. Commun., vol. COM-27, pp. 1456-1466, October 1979.

8. L. Kleinrock, Queueing Systems, Volume 2: Computer Applications, New York: John Wiley & Sons, 1976.

9. M. Schwartz, Computer-Communication Network Design and Analysis, Englewood Cliffs, NJ: Prentice-Hall, 1977.

10. W. Chou, ed., Computer Communications, vol. I, Principles, Englewood Cliffs, NJ: Prentice-Hall, 1983.

11. IEEE Transactions on Communications--Special Issue on Spread Spectrum Communications, vol. COM-30, part I, May 1982.

12. C. E. Cook and H. S. Marsh, "An Introduction to Spread Spectrum," IEEE Communications Magazine, vol. 21, pp. 8-16, March 1983.

13. M. B. Pursley, "Coding and Diversity for Channels with Fading and Pulsed Interference," Proc. 16th Annual Conf. on Information Sciences and Systems, Princeton University, pp. 413-418 March 1982.

14. M. B. Pursley, "Throughput of Frequency-Hopped Spread-Spectrum Communications for Packet Radio Networks," Proc. 17th Annual Conf. on Information Sciences and Systems, The Johns Hopkins University, pp. 550-556, March 1983.

15. B. Hajek, "Recursive Retransmission Control -- Application to a Frequency-Hopped Spread-Spectrum System," Proc. 16th Annual Conference on Information Sciences and Systems, Princeton University, pp. 116-120, March 1982.

16. J. E. Wieselthier and A. Ephremides, "Throughput Increase in Frequency Hopped Multiple Access Channels by Means of Discrimination Against Partially Overlapping Interference," submitted to IEEE Trans. on Commun., also to appear as Naval Research Laboratory Memorandum Report.

17. D. H. Davis and S. A. Gronemeyer, "Performance of Slotted ALOHA Random Access with Delay Capture and Randomized Time of Arrival," IEEE Trans. Commun., vol. COM-28, pp. 703-710, May 1980

18. J. E. Wieselthier and A. Ephremides, "A Combinatorial Technique for the Analysis of Framed Contention-Based Multiple Access Protocols," Proc. 18th Annual Conf. on Information Sciences and Systems, Princeton University, March 1984.

19. L. G. Roberts, "Dynamic Allocation of Satellite Capacity Through Packet Reservation," AFIPS Conference Proc., 1973 National Computer Conference, Vol. 42, pp. 711-716, 1973.

20. J. E. Wieselthier and A. Ephremides, "A New Class of Protocols for Multiple Access in Satellite Networks," IEEE Trans. Automatic Control, vol. AC-25, pp. 865-879, October 1980.

21. W. Feller, An Introduction to Probability Theory and its Applications, Third Edition, New York: John Wiley & Sons, Inc., revised 1970.

DEPARTMENT OF THE NAVY

NAVAL RESEARCH LABORATORY
Washington, D.C. 20375-5000